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Manual Method of Predicting Highway Traffic Noise and Sound Barrier Performance

(1978 FHWA Model)

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Contents

		Page
1/	Introduction	1
2/	Notation	3
3/	Subtending Angle ϕ and its Modification $\bar{\phi}$ for Absorbtive and Partially Absorbtive Ground Cover	4
	Ground Cover Coefficients	8
	Free Field Noise Prediction	9
	Example for Free Field Prediction	10
	Deviation of the Equation for Free Field Noise Prediction	13
	Reference Energy Mean Emission Level	13
	Adjustments for Traffic Flow, Distance, and for Finite Roadways or Subtending Angle of Segment	15
	Hourly Equivalent Sound Level L_{eq}	16
4/	Sound Attenuation of Noise Barrier Segments	17
	Sound Barrier Insertion Loss	21
Example		24
Appendix		A1

1/ Introduction

In 1978 the U.S. Department of Transportation, Federal Highway Administration published a comprehensive volume describing and deriving a manual method of highway noise prediction, FHWA Report RD-77-108, referred to in this paper as the "FHWA Report".

The special merit of this FHWA prediction model is the fact that it is based on first principles of acoustics. It has a minimum of empirical, statistically based input, such as average noise emission levels of vehicle types at various speeds. As such input is clearly defined, the FHWA model is the most flexible with regard to future changes in noise emission standards or other technical changes, or for the calculation of special cases.

Thus, in spite of numerous traffic noise prediction methods already being used, it is of great value to work with this new method, if one intends to keep up with the state of the art.

In studying the FHWA Report the author found that the free field prediction of noise along roads and highways in open, plane areas, can be simplified by turning the method into a few basic equations, assuming a uniform speed for all classes of vehicles.

Using these equations, the equivalent sound level (L_{eq}) can be calculated or programmed by electronic hand calculators very comfortably.

When speeds of vehicle classes differ, the corresponding equations are only slightly more complicated, but are also presented.

The prediction model published in the FHWA Report is based on the vehicle noise emission levels of cars, and medium and heavy trucks at a reference distance of 15 m. The noise emission level modelling for heavy trucks is different than in previously used prediction methods, which is an other reason for studying the new model.

Another important finding is that there is no theoretical or practical reason for restricting the ground cover absorbtion factor, α, to only two values (α=0, α=0.5). By introducing the concept of modified subtending angle for segments of the noise field, the factor α can be easily treated as a full variable.

Other contributions are

- a simple diagram for determining noise barrier attenuation Δ, for barrier segments (instead of tables)

- additional equations obtained by curve fitting for simplified electronic desk calculator programming

With these combinations the usage of the FHWA method for designers and environmental planners should become easy.

2/ Notation

V = total traffic on the road or on the part of the highway being considered, in vehicles per hour

p = Fraction of car traffic (Subscript A), for instance, p = 0.85 means that cars represent 85% of V (P=85)

q = fraction of medium truck traffic (Subscript MT)

r = fraction of heavy truck traffic (Subscript HT)

P,Q,R = percentages of car, medium truck, and heavy truck traffic respectively

S = average traffic speed, in km/h, assumed to be uniform

D_O = reference distance from centre line of traffic, D_O = 15 m

D_N = horizontal distance from the noise source to the centre of the nearest lane, in metres

D_F = horizontal distance from the noise source to the centre of the farthest lane, in metres

D_E = D_N D_F = equivalent lane distance, in metres

L = hourly reference energy emission level, in dBA

L_{eq} = equivalent sound level, in dBA

α = ground cover coefficient, according to the FHWA Report:

α = 0 for hard, reflective surfaces

α = 0.5 for soft, absorptive surfaces

ϕ = subtending segment angle in degrees, viewed from the point of the receiver towards the road.

ϕ_1 ϕ_2 = subtending angles for a segment (see also FHWA Report), refer to Figure 1

ϕ'_1, ϕ'_2 = modified angles for a segment

$\overline{\phi}$ = equivalent subtending angle, $\overline{\phi}$ being reduced because of soft ground cover, refer to the following discussion

Δ = noise attemation for a segment from a sound barrier parallel to the highway, in dBA

N_O = Fresnel number for path length difference δ

δ = path length difference perpendicular to the road axis, refer to Figure 6.

I sound barrier insertion loss, in dBA

3/ Subtending Angle, ϕ, and its Modification, $\bar{\phi}$, for Absorbtive or Partially Absorbtive Ground Cover.

Orientation of Highway Segment

The following procedure will be used to determine the angular relationship between the roadway segment and an observer facing the segment. (Refer to Figure 1 and 2)

Step 1. Draw a perpendicular line from the roadway, or the roadway extension to the observer. All angles are measured from this perpendicular.

Step 2. Draw a line from the observer to the left most end of the highway segment. The angle measured from the perpendicular drawn in Step 1 to the line connecting the observer and the left most end of the roadway segment is ϕ_1. If ϕ_1 is measured to the left of the perpendicular it is negative. If ϕ_1 is measured to the right of the perpendicular it is positive.

Step 3. Draw a line from the observer to the right most end of the highway segment. The angle measured from the perpendicular drawn in Step 1 to the line connecting the observer and the right most end of the highway segment is ϕ_2. If ϕ_2 is measured to the left of the perpendicular, it is negative, if ϕ_2 is measured to the right of the perpendicular it is positive.

Step 4. Check the angles ϕ_1 and ϕ_2 by use of the equation

$$\phi = \phi_2 - \phi_1 \qquad (1)$$

where

ϕ_1 and ϕ_2 are the angles in degrees identified in Steps 1-3 above. In all cases ϕ will be positive and will be numerically equal to the included angle subtended by the roadway relative to the receiver.

The definition of ϕ_1, and ϕ_2 for typical segments near a sound barrier and the calculation of the subtending angles ϕ is illustrated in Figure 1. Figure 2 shows a special case for a "turning away" roadway.

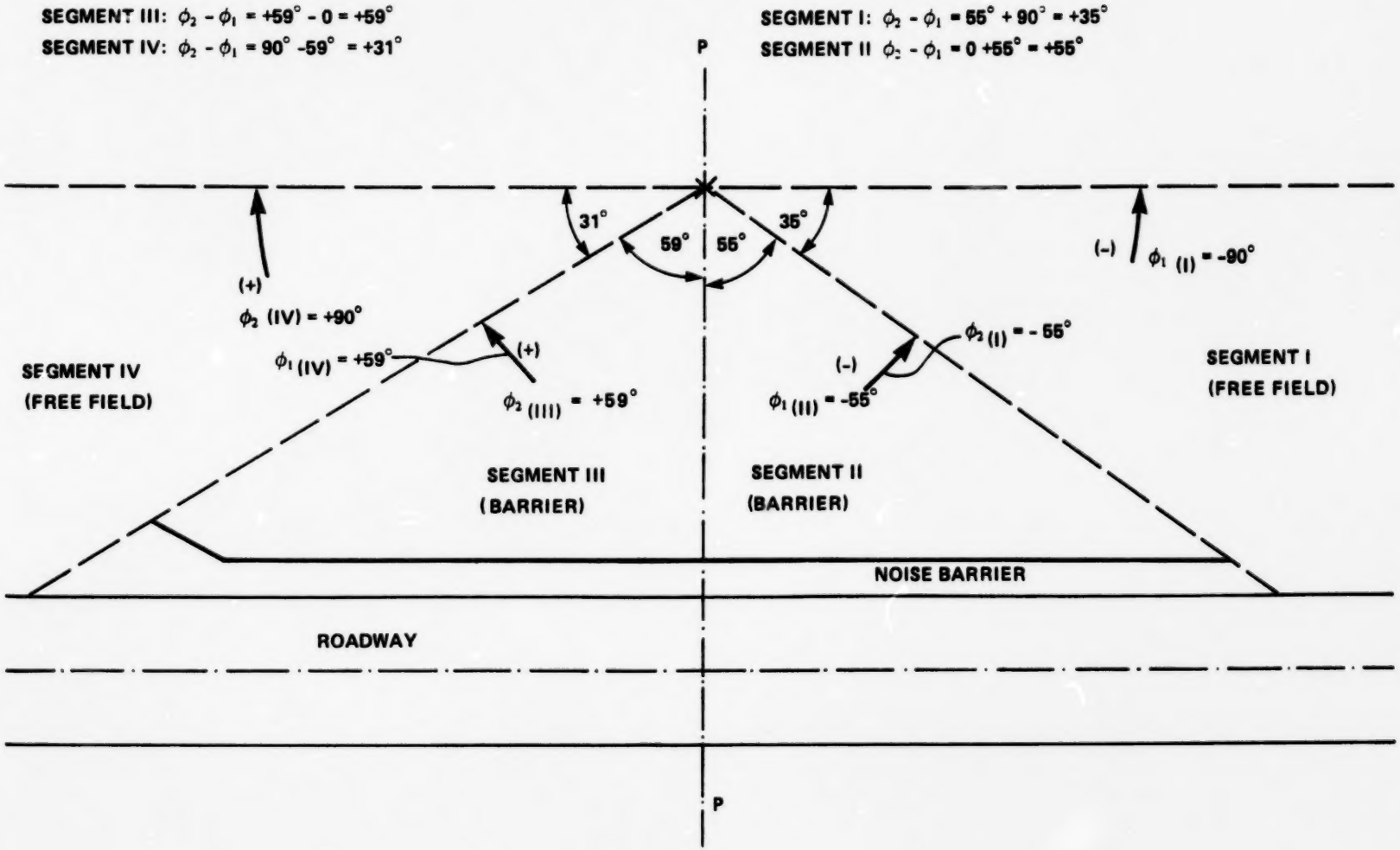


Figure 1/ Subtending Angles for IV Segments Near Sound Barrier

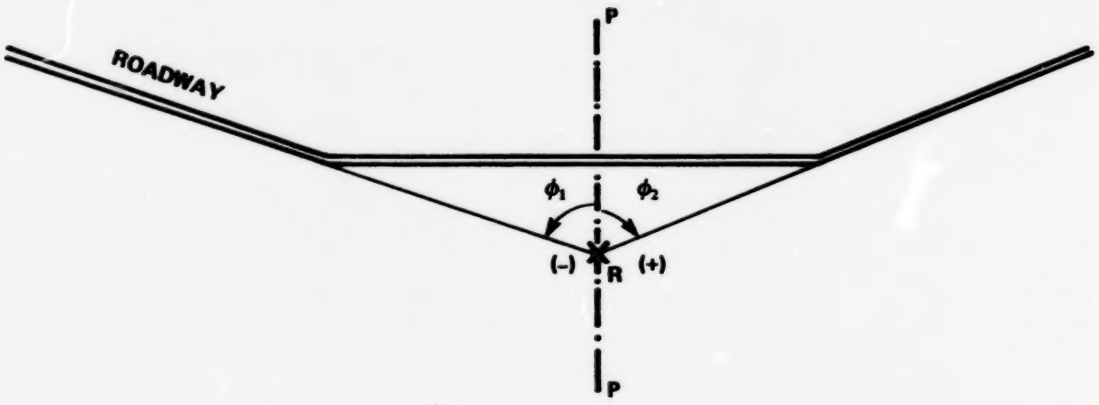


Figure 2/ Subtending Angle for "Turning Away" Roadway

The subtending angle is always calculated as follows:

$$\phi = \phi_2 - \phi_1 \qquad (1)$$

where ϕ_1 and ϕ_2 are measured from the line P-P perpendicular to the road, at the receiver position R, positive in the clockwise direction. Note that the angle ϕ_1 in Figure 2 is negative.

In case of soft, absorbtive ground cover, the angles ϕ_1 and ϕ_2 are to be modified, and a modified or equivalent subtending angle is calculated as follows:

$$\overline{\phi} = \phi_2' - \phi_1' \qquad (2)$$

The modified angles ϕ_1' and ϕ_2' have the same signs as the actual angles ϕ_1 and ϕ_2, respectively. The absolute values of ϕ_1 and ϕ_2 can be determined from Table 1, which is a solution of the integral.

$$\phi' = \frac{180^\circ}{\pi} \int_0^{\phi} (\cos \phi)^{\alpha} \, d\phi \qquad (3)$$

Table 1/ Absolute Values of ϕ'

	$\alpha = 0$	$\alpha = 0.25$	$\alpha = 0.5$	$\alpha = 0.75$
0°	0	5.000	5.000	5.000
5°	5	4.998	4.997	4.995
10°	10	9.987	9.975	9.962
15°	15	14.957	14.914	14.872
20°	20	19.898	19.796	19.696
25°	25	24.799	24.601	24.406
30°	30	29.651	29.309	28.975
35°	35	34.442	33.901	33.374
40°	40	39.161	38.353	37.576
45°	45	43.793	42.645	41.554
50°	50	48.325	46.754	45.278
55°	55	52.741	50.654	48.723
60°	60	57.021	54.318	51.860
65°	65	61.141	57.714	54.659
70°	70	65.072	60.805	57.091
75°	75	68.772	63.544	59.119
80°	80	72.178	65.866	60.703
85°	85	75.173	67.664	61.785
90°	90	77.150	68.606	62.237

Note: For $\alpha = 1$ $\quad \phi' = \frac{180}{\pi} \sin \phi$

Approximation for calculator programming (within ±1% of ϕ')

$$\phi' \cong \phi - (47.4\, \alpha^{0.8}) \left(\frac{\phi}{100}\right)^3 \qquad (4)$$

or refer to Appendix, Equations A-6.1, A-6.2, A-6.3

Ground Cover Coefficients

$\alpha = 0$ reflective ground cover, such as paved parking lots, ice covered ground, collector & residential streets

$\alpha = 0.25$ moderately reflective ground cover, such as bare soil, minor patches of grass, partially paved back yards, parking lots interspersed with lawns

$\alpha = 0.5$ absorptive ground cover, such as lawns and soft soil fields, back yards with plants, flowers and small shrubs

$\alpha = 0.75$ very absorptive ground cover, such as back yards with trees and shrubs, corn fields, etc.

Free Field Noise Prediction

Simplified equations are presented for variable ground cover, but for equal speeds of trucks and cars. With these equations the noise can be predicted for a receiver standing on a horizontal plane ground adjacent or at some distance from the highway.

$$Le_q = 10 \log\left[\frac{\bar{\phi}}{15} V S^2 K \left(\frac{15}{D_E}\right)^{1+\alpha}\right] \qquad (5)$$

where

$$K = \frac{pS}{1040} + \frac{q\sqrt{S}}{9.6} + \frac{23.5\, v}{\sqrt{S}} \qquad (6)$$

$\bar{\phi}$ is the equivalent subtending angle and must be calculated from Equation (2), using the definitions from Figure 1 for ϕ_1, and ϕ_2, and Table 1 for determining ϕ_1', and ϕ_2'.

Whenever the noise for traffic components has to be calculated separately, the following expressions for K must be used:

cars: $K_p = \frac{pS}{1040}$ instead of K (6a)

medium trucks: $K_q = \frac{q\sqrt{S}}{9.6}$ instead of K (6b)

heavy trucks: $K_v = \frac{23.5\, v}{\sqrt{S}}$ instead of K (6c)

If the reference speed for cars, medium and heavy trucks differs, Equations (A-1) to (A-5) must be used, which are directly derived from the equations in the FHWA Report without simplification.

Example for Free Field Prediction

The following example for a highway and observer as shown in Figure 3 illustrates the usage of Equations (1) to (6). The angles ϕ_1 and ϕ_2 are measured from the centre line 0-A, perpendicular to the road tangent, to the lines of view parallel to the road. There is a slight difference in the prediction, depending on assumptions about ground cover.

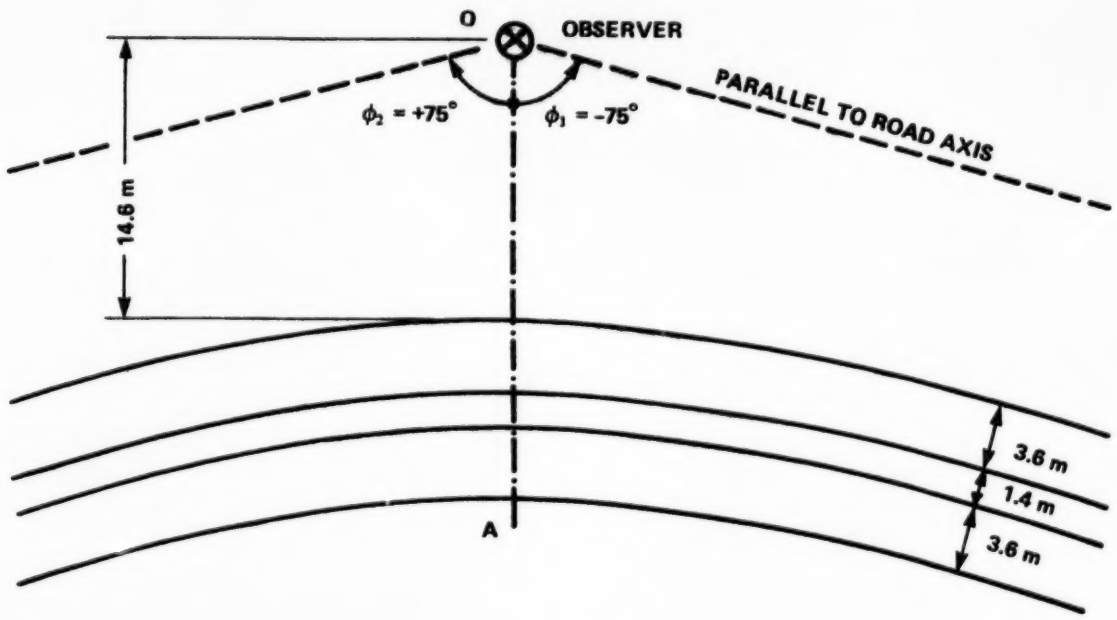


Figure 3/ Example

a) For reflective hard ground cover, $\alpha = 0$

Hourly Traffic: 1800 cars, 120 medium trucks, 80 heavy trucks

S = 50 km/h $\alpha = 0$, reflective ground surface

V = 1800 + 120 + 80 = 2000 vehicles per hour

$p = \frac{1800}{2000} = 0.90$ $q = \frac{120}{2000} = 0.06$

$r = \frac{80}{2000} = 0.04$ $\phi = 75° - (-75°) = 150°$; (Fig 3)

$D_E = \sqrt{(14.6 + 1.8)\ (14.6 + 3.6 + 1.4 + 1.8)} = 18.7$ m

$K = \frac{0.9 \times 50}{1040} + \frac{0.06\sqrt{50}}{9.6} + \frac{23.5 \times 0.04}{\sqrt{50}} = 0.220$

$L_{eq} = 10 \log [150 \times 2000 \times 50^2 \times 0.220 / 18.7] = 69.5$ dBA

b) For absorbtive, soft ground cover, $\alpha = 0.5$
Speed and traffic composition as before

D_E = 18.7 m (as before) K = 0.220 (as before)

ϕ_2 = 75 from Table 1: $\phi_2' = 63.544 \cong 63.6$

ϕ_1 = -75 from Table 1: $\phi_1' = -63.544 \cong -63.6$

Equivalent or modified subtending angle:

$\overline{\phi} = \phi_2' - \phi_1' = 63.6 - (-63.6) = 127.2$

Using Equation (5):

$$L_{eq} = 10 \log \left[\frac{127.2}{15} \times 2000 \times 50^2 \times .220 \times \left(\frac{15}{18.7}\right)^{1.5} \right]$$

$= 10 \log (6\ 701\ 361) = 68.3$ dBA

The difference between the two cases with and without soft ground cover is only 1.2 dBA, because of the short distance

Note:
The calculation of $\bar{\phi} = \phi_2' - \phi_1'$ by means of Table 1, modifying ϕ_1 to ϕ_1', corresponds to the solution of the integral

$$\bar{\phi} = \int_{\phi_1}^{\phi_2} (\cos \phi)^{\alpha} \, d\phi$$

Refer to FHWA Report, Equation (A-64).

Deviation of the Equation for Free Field Noise Prediction

Reference Energy Mean Emission Levels

The hourly reference energy mean emission levels of cars, medium trucks, and heavy trucks are represented by three equations (FHWA Report):

$(L_A) = 38.1 \log S - 2.4$ for cars (A)

$(L_{MT}) = 33.9 \log S + 16.4$ for medium trucks (MT)

$(L_{HT}) = 24.6 \log S + 38.5$ for heavy trucks (HT)

Equations (1) to (5) of this report here have been derived by modifying these (L) expressions, transforming them into sound pressure energy levels ($10^{L/10}$), and then adding up all energy levels for the particular composition of traffic. The equations for (L) have been modified as follows (exact values, leading to Equations (1) to (5) presented before):

$L_A = 40 \log S - 6.110932$ for cars (A)

$L_{MT} = 35 \log S + 14.236689$ for medium trucks (MT)

$L_{HT} = 25 \log S + 37.77008$ for heavy trucks (HT)

There are small deviations beteween these two sets of functions for L which are illustrated in Figure 4 (dashed lines versus solid lines, FHWA Level 2). For the modified L equations the direct sound pressure energy levels are derived by an anti-log transformation, $10^{L/10}$, as follows:

for cars: $C = 10^{(L_A/10)} = 0.2448538\ S^4$ (7)

for medium trucks: $M = 10^{(L_{MT}/10)} = 26.525823\ S^{3.5}$ (8)

for heavy trucks: $H = 10^{(L_{HT}/10)} = 5984.2257\ S^{2.5}$ (9)

The functions C, M, and H represent the direct energy levels of sound pressures, and can therefore be added arithmetically, after weighing them by the traffic fractions p, q, and r.

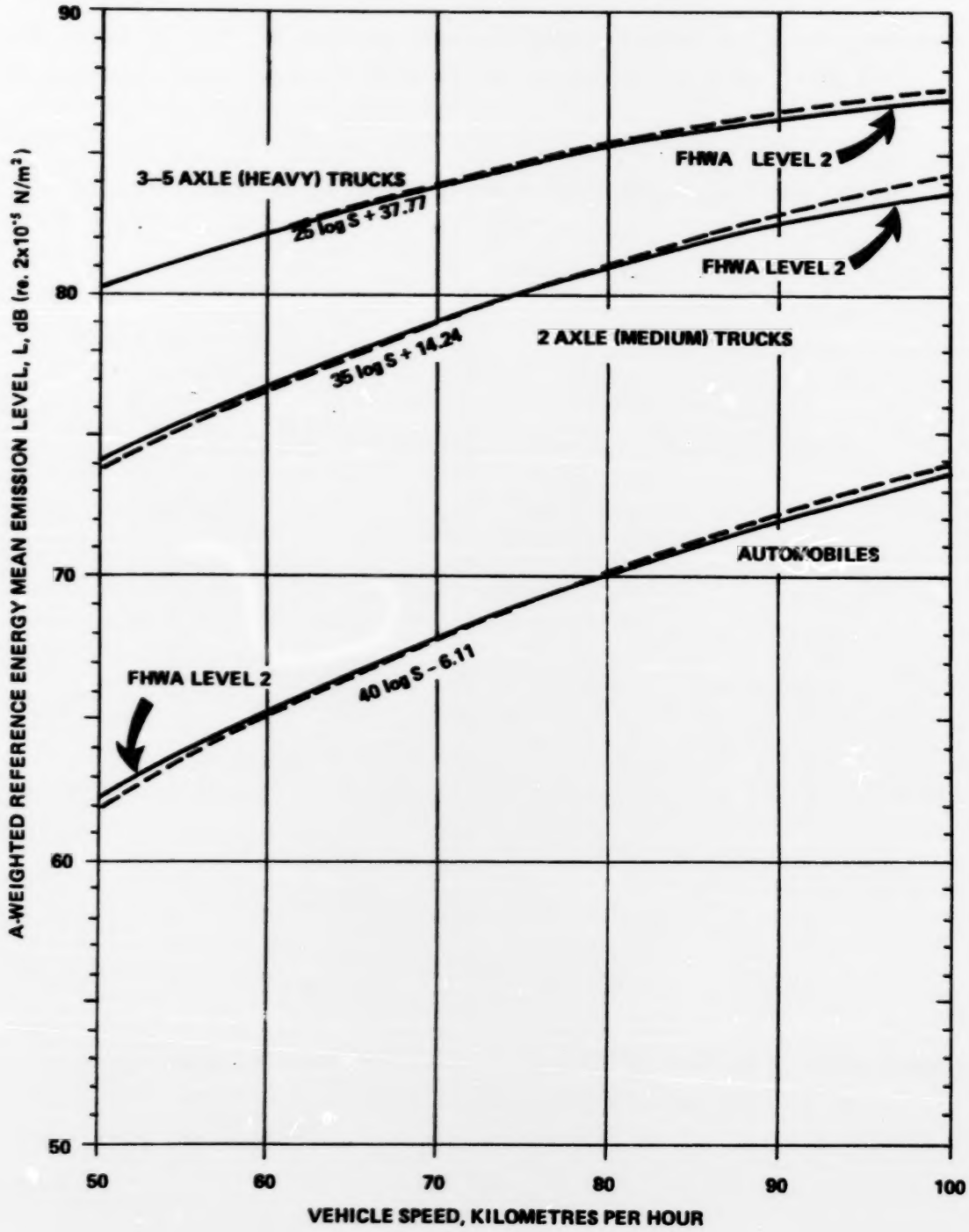


Figure 4/ Comparison of "A" Weighted Reference Emission Levels

Adjustments for Traffic Flow, Distance,
and for Finite Roadways or Subtending Angle of Segment

In terms of actual energy levels, the adjustments are expressed as factors after adding the weighted contributions from the vehicular traffic components.

1) Traffic flow adjustment factor, including vehicle noise emission components:

$$(Cp + Mq + Hr)\ \frac{\pi D_o V}{100\ S}$$

2) Distance adjustment factors

$$\frac{D_o}{D_E} \ldots\ldots \text{for} \quad \alpha = 0$$

$$\left(\frac{D_o}{D_E}\right)^{1+\alpha} \ldots\ldots \text{for} \quad \alpha > 0$$

3) Finite roadway adjustment factors, or factor for subtending angle ϕ:

$$\phi/180 \ldots \text{for} \quad \alpha = 0$$

$$\phi/180 \ldots \text{for} \quad \alpha > 0$$

The modifications illustrated in Figure 4 lead to a very simple expression for the traffic coefficient K, represented by Equations (5) and (6).

Hourly Equivalent Sound Level L_{eq}

The deviation is carried out for Equation (5). The hourly equivalent sound level can be written down by combining all pertinent factors:

$$Leq = 10 \log \left[\frac{\pi \; D_o \; V \; \phi}{100 \; S \; 180^o} \; (C_p + M_q + H_r) \left(\frac{D_o}{D_E} \right)^{1+\alpha} \right] \quad ; \quad (10)$$

The value $\frac{1000 \times 180}{\pi \; D_o^2}$ is equal to 245.64791

and Equations (7), (8), and (9) are now substitued into Equation (10), which leads directly to Equation (5) and (6), with $D_o = 15$.

4/ Sound Attenuation of Noise Barrier Segments

For a receiver position, as shown in Figure 1, the noise from all segments (I to IV) is combined and added to a total level. Before this combination, segments are treated separately, and they may have non-attenuated "free field" noise contributions and/or contributions attenuated by a barrier. A noise attenuation value, Δ, has to be subtracted from the "free field" contribution with $\alpha = 0$, whenever a noise barrier is present in this segment. The noise attenuation, Δ, for each barrier segment (such as Segment II and Segment III) is basically a function of the Fresnel number N_o and the subtending angle ϕ measured from the line perpendicular to the road axis (refer to Figure 1). The Fresnel number is calculated as follows.

$$N_o = 2 \left(\frac{f \delta}{\lambda} \right) = 2 \left(\frac{550 \delta}{343} \right) = 3.21 \delta \qquad (11)$$

where

f = frequency of sound waves in Hz, f=550 Hz is being selected as representative frequency for noise

λ = velocity of sound in air, 343 m/s

δ = path length difference, in metres, between noise source and receiver, perpendicular to the road axis, comparing a direct path line C and an indirect path line over top of the barrier (A + B), refer to Figure 5, δ = A+B-C.

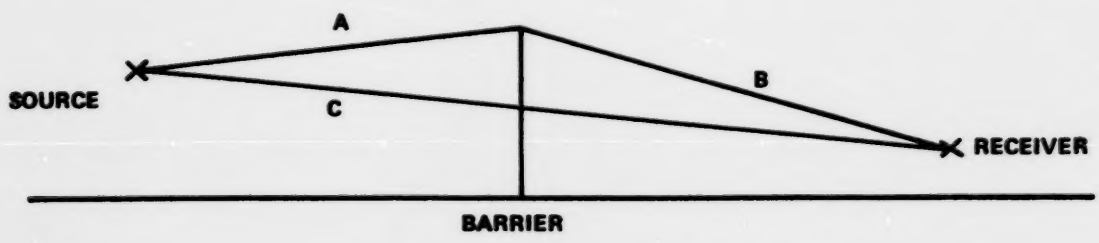


Figure 5/ Path Length Difference

To calculate the path length difference, there is a need to organize the calculations in terms of horizontal distances and heights above the road surface. Denote in accordance with Figure 6.

h_S = level of noise source above the road surface, in metres

h_R = level of receiver of noise above the road surface, in metres

h_T = level of barrier top above the road surface, in metres.

d_S = horizontal distance of noise source from a vertical plane through the barrier top, in metres

d_R = horizontal distance of receiver from a vertical plane through the barrier top, in metres.

Then: $\delta = A + B - C$

$$\delta = \sqrt{(h_T - h_S)^2 + d_S^2} + \sqrt{(h_T - h_R)^2 - d_R^2} - \sqrt{(h_S - h_R)^2 - (d_S - d_R)^2} \qquad (12)$$

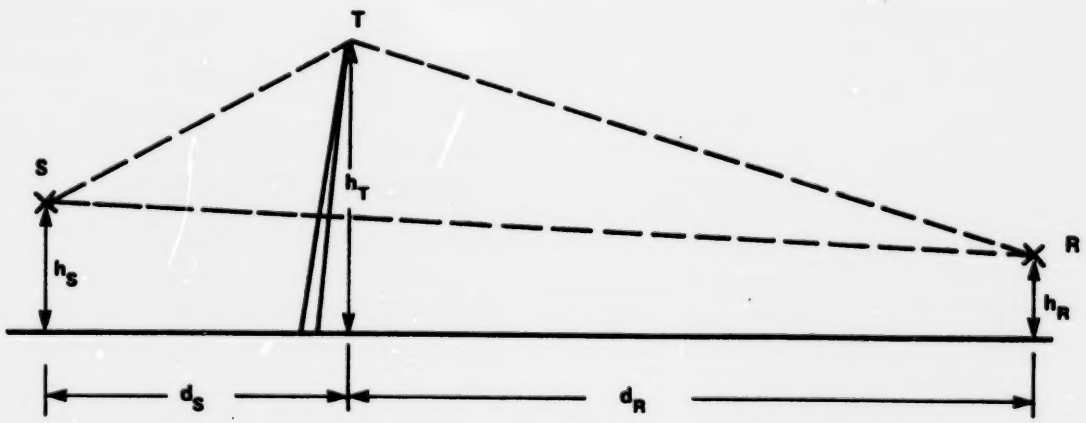


Figure 6/ Organizing the Calculation of δ

The following assumptions are made for receiver and source levels above ground or road surfaces respectively:

Noise from cars:	$h_{SA} = 0$
from medium trucks:	$h_{SMT} = .7$ m
from heavy trucks:	$h_{SHT} = 2.44$ m
Receiver above ground: (may be lower or higher than 1.5 m above the road surface)	$h_R = 1.5$ m

For a noise barrier segment left or right of the line perpendicular to the road axis, such as Segment II or III in Figure I, the noise attenuation value, Δ, can be determined from the diagram in Figure 7, which is a simplified (plotted) representation of Tables B-35 to B-71 of the FHWA Report.

The diagram can be used only for segments, such as II or III in Figure 1, with one angle being zero, i.e. bordering the line P-P perpendicular to the road axis.

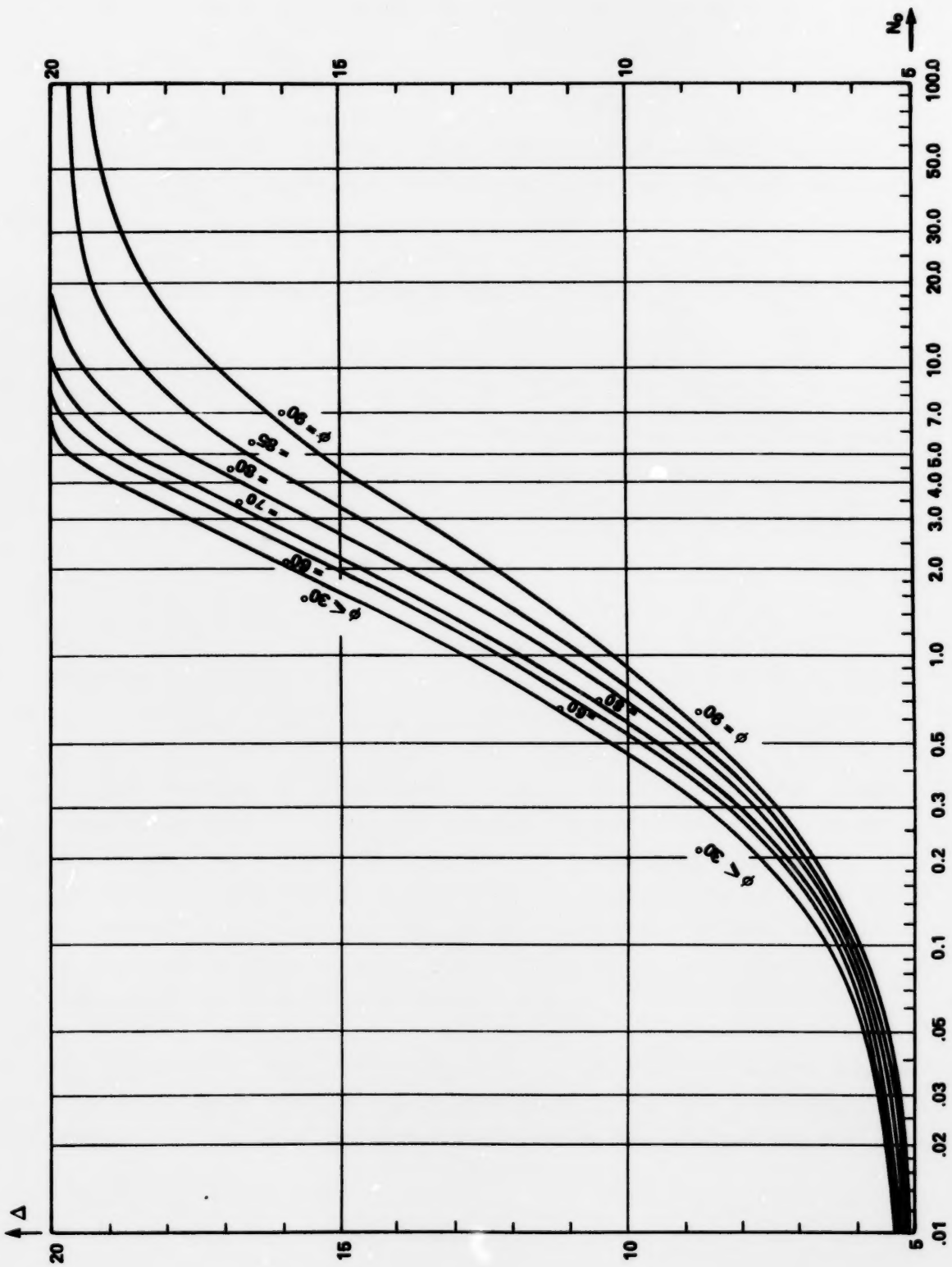


Figure 7/ Noise Barrier Attenuation Δ Versus N_o

Sound Barrier Insertion Loss

For each segment containing a barrier, the sound barrier insertion loss, I, can be calculated as follows:

$$I = Leq_{(f)} - Leq_{(\Delta)} \qquad (13)$$

Where $Leq_{(f)}$ = segmental free field noise without the presence of the barrier, but, as the case may be, with ground cover, in dBA,

To calculate $Leq_{(f)}$ use Equation (5).

Where $Leq_{(\Delta)}$ = segmental noise with barrier attemation, in dBA

To calculate $Leq_{(\Delta)}$, use Equation (5), but set $\alpha = 0$ and subtract the noise attenuation value, Δ.

$$Leq_{(\Delta)} = 10 \log\left[\phi \, V S^2 K / D_{E(\Delta)}\right] - \Delta \qquad (14)$$

Note that for $\alpha = 0$, the subtending angle is not being modified, i.e. $\bar{\phi} = \phi$.

If the barrier is a thin wall structure, the segmental sound barrier insertion loss may have to be modified downwards by a small amount. This modification of I has been reported elsewhere. Depending on the desired accuracy of the result, a thin-wall structure may be defined as having an average sound transmission loss of less than 32 dB, or of less than (Δ + 10) dB, which is less stringent.

In calculating $D_{E(\Delta)}$, it should be noted that the noise source distances must now be taken from the top of the barrier; therefore, in case of sound barriers being present (Index Δ):

$$D_{E(\Delta)} = d_R + \sqrt{d_{SN} \times d_{SF}} \qquad (15)$$

for d_S and d_R refer to Figure 6.

where N = subscript denoting "nearest lane"

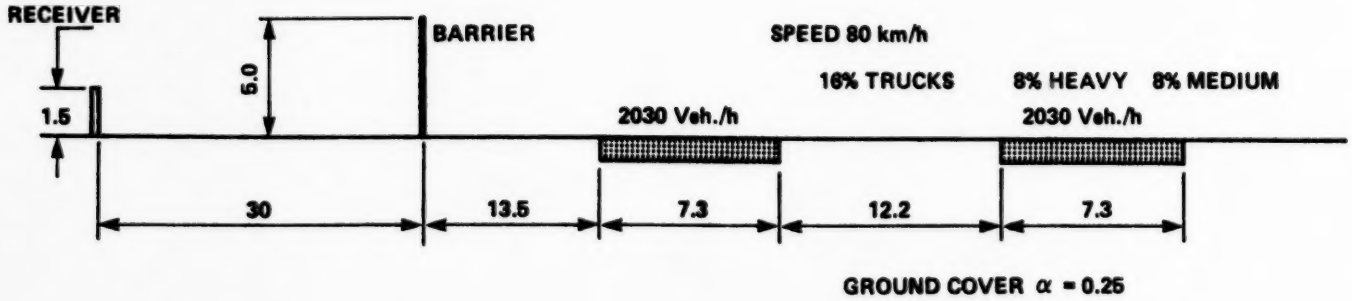
Finally, the following equation is used to combine and add noise from various sources and/or segments:

$$\text{total } L_{eq} = 10 \log \left[\sum_{i=1}^{n} 10^{L_{eq_i}/10} \right] \qquad (16)$$

where L_{eq_i} = noise level from source i, in dBA

n = number of noise sources to be combined

OTTAWA QUEENSWAY



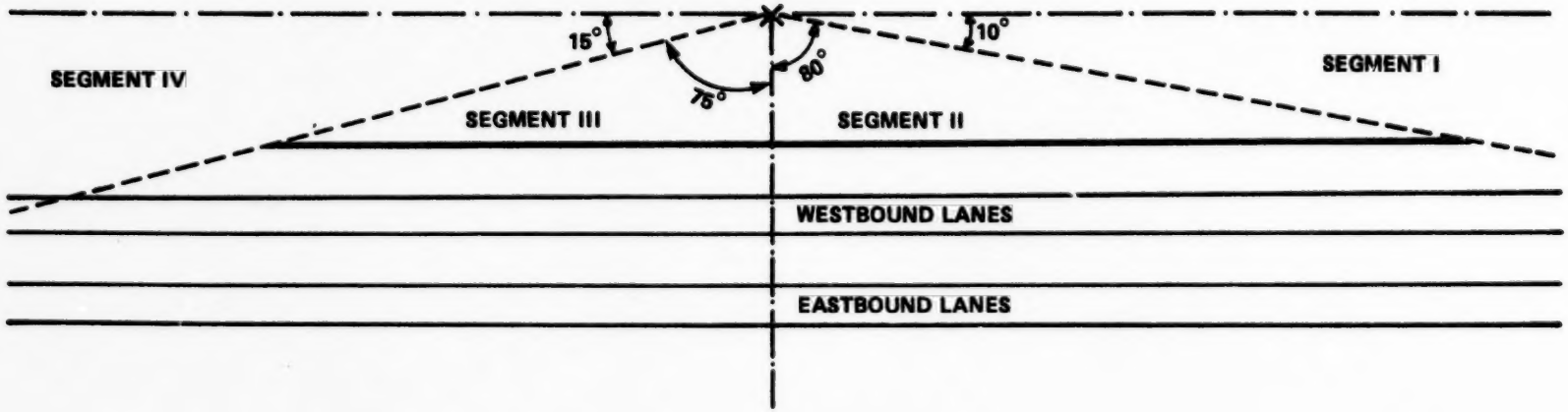


Figure 8/ Example (Ottawa Queensway)

Example:

An example is shown in Figure 8, for a typical barrier of limited length along the Ottawa Queensway. Calculations are requested for 4 Segments, separately for east and westbound lanes. For Segments II and III reperation is needed also for vehicle types, since noise barrier attemation, Δ, depends on the height of the standard noise sources (cars, medium trucks, heavy trucks).

Equivalent lane distances:

free field, east bound lanes $D_E = \sqrt{64.825 \times 68.475'} = 66.625$ m

free field, west bound lanes $D_E = \sqrt{45.325 \times 48.975'} = 47.115$ m

barrier, east bound lanes $D_{E(\Delta)} = 30 + \sqrt{34.825 \times 38.475'} = 66.605$ m

barrier, west bound lanes $D_{E(\Delta)} = 30 + \sqrt{15.325 \times 18.975'} = 47.053$ m

Traffic coefficients K, for all segments, east-and westbound lanes, using Equation (6)

for cars: $K_p = (0.84 \times 80)/1040 = 0.0646$

for medium trucks: $K_q = (0.08 \times \sqrt{80})/9.6 = 0.0745$

for heavy trucks: $K_r = (23.5 \times 0.08)/\sqrt{80} = 0.2102$

Total: $K = K_p + K_q + K_r = 0.3493$

Subtending angles and modified subtending angles

Segment I: $\phi_1 = -90°$ $\phi_2 = -80°$

$\phi = -80 + 90 = +10°$

$\bar{\phi} = -72.178 + 77.150 = +4.972$

Segment II: $\phi_1 = -80°$ $\phi_2 = 0°$

$\phi = 0 + 80° = 80°$

$\bar{\phi} = 0 + 72.178 = + 72.178$

Segment III: $\phi_1 = 0°$ $\phi_2 = 75°$

$\phi = +75 - 0 = +90°$

$\bar{\phi} = +68.772 -0 = +68,772$

Segment IV: $\phi_1 = +75°$ $\phi_2 = +90°$

$\phi = +90 - 75 = +15$

$\bar{\phi} = +77.150 - 68.772 = +8.378$

Refer to Equation (1) and Figure (1), then using Table 1.

Noise levels of Segments I and IV, refer to Equation (5) & (16)

I) Eastbound lanes:

$$L_{eq_I} = 10 \log \left[\frac{4.972}{15} \times 2030 \times 80^2 \times 0.3493 \times \left(\frac{15}{66.625} \right)^{1.25} \right]$$

$$= 10 \log \left[233\ 282.42 \right] = 53.679 \cong 53.7 \text{ dBA}$$

Westbound lanes:

$$L_{eq_I} = 10 \log \left[\frac{4.970}{15} \times 2030 \times 80^2 \times 0.3493 \times \left(\frac{15}{47.115} \right)^{1.25} \right]$$

$$= 10 \log \left[359\ 587.68 \right. = 55.558 \cong 55.6 \text{ dBA}$$

$$\text{total } L_{eq_I} = 10 \text{ Log } (10^{5.3679} + 10^{5.5558}) = 57.730 \cong 57.7 \text{ dBA}$$

IV) Eastbound lanes:

$$L_{eq_{IV}} = 10 \text{ Log } \left[\frac{8.378}{15} \times 2030 \times 80^2 \times 0.3493 \times \left(\frac{15}{66.625} \right)^{1.25} \right]$$

$$= 10 \text{ Log } [393\ 089.32] = 55.945 \cong 55.9 \text{ dBA}$$

Westbound lanes:

$$L_{eq_{IV}} = 10 \text{ Log } \left[\frac{8.378}{15} \times 2030\ 80^2 \times 0.3493 \times \left(\frac{15}{47.115} \right)^{1.25} \right]$$

$$= 10 \text{ Log } \left[606\ 162.09 \right] = 57.826 \cong 57.8 \text{ dBA}$$

$$\text{total } L_{eq_{IV}} = 10 \text{ Log } \left(10^{5.5945} + 10^{5.7826} \right) = 59.997 \cong 60.0 \text{ dBA}$$

Free Field Noise Levels of Segments II and III

Similarly, using Equation (5) and (16), the results are

Total L_{eqII} = 69.349 $\cong$ 69.3 dBA

Total L_{eqIII} = 69.139 $\cong$ 69.1 dBA

Perpendicular path length difference over barrier in Segments II and III, refer to Equation (12) and Figure (6)

Eastbound lanes

$$d_R = 30 \text{ m} \qquad d_S = 66.605 - 30 = 36.605 \text{ m}$$

$$\delta_p = \sqrt{5^2 + 36.605^2} + \sqrt{(5-1.5)^2 + 30^2} - \sqrt{1.5^2 + 66.605^2} = 0.526 \text{ m}$$

$$\delta_q = \sqrt{5-0.7^{\,2} + 36.605^2} + \sqrt{(5-1.5)^2 + 30^2} - \sqrt{1.5-0.7^{\,2} + 66.605^2} = 0.450 \text{ m}$$

$$\delta_r = \sqrt{(5-2.44)^2 + 36.605^2} + \sqrt{(5-1.5)^2 + 30^2} - \sqrt{(2.44-1.5)^2 + 66.605^2} = 0.285$$

Westbound Lanes

$$d_R = 30 \text{ m} \qquad d_S = 47.053 - 30 = 17.053 \text{ m}$$

$$\delta_p = \sqrt{5^2 + 17.053^2} + \sqrt{(5-1.5)^2 + 30^2} - \sqrt{1.5^2 + 47.053^2} = 0.897 \text{ m}$$

$$\delta_q = \sqrt{(5-0.7)^2 + 17.053^2} + \sqrt{(5-1.5)^2 + 30^2} - \sqrt{(1.5-0.7)^2 + 47.053^2} = 0.730 \text{ m}$$

$$\delta_r = \sqrt{(5-2.44)^2 + 17.053^2} + \sqrt{(5-1.5)^2 + 30^2} - \sqrt{(2.44-1.5)^2 + 47.053^2} = 0.385 \text{ m}$$

Noise abatement values, using diagrams in Figure 7

				Segment II	Segment III
EASTBOUND	Case	δ	N = 3.21	$\Delta(80°)$	$\Delta(75°)$
	P	.526	1,6885	13.1	13.4
	q	.450	1,4445	12.5	12.8
	r	.285	.9149	10.85	11.1
WESTBOUND	p	.897	2.879	15.25	15.8
	q	.730	2.343	14.4	14.8
	r	.385	1.236	12.0	12.3

Noise levels behind barrier from Segment II, according to Equation (14)

Eastbound lanes

$$L_{eq_p} = 10 \log \left[80 \times 2030 \times 80^2 \times 0.0646/66.605\right] - 13.1$$

$$= 60.035 - 13.1 \cong 46.9$$

$$L_{eq_q} = 10 \log \left[80 \times 2030 \times 80^2 \times 0.0745/66.605\right] - 12.5$$

$$= 60.654 - 12.5 \cong 48.2$$

$$L_{eq_r} = 10 \log \left[80 \times 2030 \times 80^2 \times 0.2102/66.605\right] - 10.85$$

$$= 65.159 - 10.85 \cong 54.3 \quad \text{dBA}$$

Westbound lanes

$$L_{eq_p} = 10 \log\left[80 \times 2030 \times 80^2 \times 0.0646/47.053\right] - 15.25$$

$$= 61.544 - 15.25 = 46.3 \text{ dBA}$$

$$L_{eq_q} = 10 \log\left[80 \times 2130 \times 80^2 \times 0.0745/47.053\right] - 14.4$$

$$= 62.163 - 14.4 = 47.8 \text{ dBA}$$

$$L_{eq_r} = 10 \log\left[80 \times 2030 \times 80^2 \times 0.0745/47.053\right] - 14.4$$

$$= 66.668 - 12.0 = 54.7 \text{ dBA}$$

Noise levels behind barrier from Seqment III

Eastbound lanes

$$L_{eq_p} = 10 \log\left[75 \times 2030 \times 80^2 \times 0.0646/66.605\right] - 13.4$$

$$= 59.744 - 13.4 = 46.4 \text{ dBA}$$

$$L_{eq_q} = 10 \log\left[75 \times 2030 \times 80^2 \times 0.0745/66.605\right] - 12.8$$

$$= 60.374 - 12.8 = 47.6 \text{ dBA}$$

$$L_{eq_r} = 10 \log\left[75 \times 2030 \times 80^2 \times 0.2102/66.605\right] - 11.1$$

$$= 64.879 - 11.1 = 53.8 \text{ dBA}$$

Westbound Lanes

$$L_{eq_p} = 10 \log\left[75 \times 2030 \times 80^2 \times 0.0646/47.053\right] - 14.8$$

$$=61.264 - 15.8 = 45.5 \text{ dBA}$$

$$L_{eq_q} = 10 \log\left[75 \times 2030 \times 80^2 \times 0.0745/47.053\right] - 14.8$$

$$= 61.883 - 14.8 = 47.1 \text{ dBA}$$

$$L_{eq_r} = 10 \log\left[75 \times 2030 \times 80^2 \times 0.2102/47.053\right] - 12.3$$

$$= 66.388 - 12.3 = 54.1 \text{ dBA}$$

Total noise from Seqment II:

$$L_{eq_{II\Delta}} = 10 \log \left[10^{4.69}+10^{4.82}+10^{5.43}+10^{4.63}+10^{4.78}+10^{5.47}\right]$$

$$= 10 \log [782\ 235.54] = 58.933 \cong \underline{58.9}$$

Total noise from Seqment III:

$$L_{eq_{III\Delta}} = 10 \log \left[10^{4.64}+10^{4.76}+10^{5.38}+10^{4.55}+10^{4.71}+10^{5.41}\right]$$

$$= 10 \log [\ 684\ 885.92\ ] = 58.356 \cong \underline{58.4}$$

Noise prediction

Seqment	Free Field		With Barrier Insertion	
I	57.7	dBA	57.7	dBA
II	69.3	dBA	58.9	dBA
III	69.1	dBA	58.4	dBA
IV	60.0	dBA	60.0	dBA
Total Equation (16)	72.7		64.9	

Barrier insertion loss: 72.6

-64.9

7.7 dBA

Appendix:

A Simple Set of Equations for Programming Electronic Desk Calculators

Free Field Noise Prediction

Based on actual FHWA equations for vehicle emission levels (no approximation).

$$L_{eq} = 10 \log \left[\frac{\bar{\varphi}}{15} \; V \; \bar{K} \; \left(\frac{15}{D_E} \right)^{1 + \alpha} \right] \qquad \text{(A-1)}$$

where:

$D_E = \sqrt{D_N \; D_F'}$ = equivalent lane distance, in meteric

$$\bar{K} = \bar{K}_A + \bar{K}_{MT} + \bar{K}_{HT} \qquad \text{(A-2)}$$

$$\bar{K}_A = (P/44253) \times S_A^{2.81} \quad \text{(cars)} \qquad \text{(A-3)}$$

$$\bar{K}_{MT} = (Q/583.36) \times S_{MT}^{2.39} \quad \text{(medium trucks)} \qquad \text{(A-4)}$$

$$\bar{K}_{HT} = .27798 \; R \; S_{HT}^{1.46} \quad \text{(heavy trucks)} \qquad \text{(A-5)}$$

S_A = car speed in km/h

S_{MT} = medium truck speed, in km/h

S_{HT} = heavy truck speed, in km/h

ALSO REFER TO PAGE 3

where $\bar{\varphi} = \varphi_2' - \varphi_1'$, as discussed before, see Table 1

$$\varphi_i' = \varphi_i \left[1 - \frac{M}{|\varphi_i|} \left(\frac{|\varphi_i|}{100} \right)^n \right] \qquad \text{(A-6)}$$

$$M = \left(90 \right) \left(\frac{0.58 \; \alpha^{0.9}}{0.58 \; \alpha^{0.9} + 1} \right) \qquad \text{(A-6.2)}$$

$$n = \frac{1}{0.134 \, \alpha + 0.225} \qquad \text{(A-6.3)}$$

Approximation for Table 1 values; deviation <0.8%

for $\alpha = 1$ the accurate solution is

$$\bar{\phi} = \frac{180}{\pi} (\sin \phi_2 - \sin \phi_1) \quad \text{(A-7)}$$

The special case of $\phi_2 = 90°$ and $\phi_1 = -90°$ has been approximated by a different equation

for $0 \leqslant \alpha \leqslant 0.75$

$$\bar{\phi} = \frac{180}{1 + 0.58 \ \alpha^{0.9}} \quad \text{(A-8)}$$

for $\alpha = -1$ the accurate solution is

$$\bar{\phi} = \frac{180}{\pi/2} \quad \text{(A-9)}$$

The ground cover coefficient is treated as a variable without contradiction. The approximation of the integral Equation (3) is accurate enough for all practical purposes.

Noise Barrier Attenuation

Presented is an approximate, curve-fitted solution of the integrals, as represented in Figure 7.

For an "infinitely" long barrier, i.e. for $\phi = 180°$, or barrier sections of $\phi = \phi_2 - \phi_1 = 90°$, left or right from the perpendicular line through the receiver location (refer to Figure 1, Line P-P) the sound barrier attenuation can be approximately calculated by

$$\Delta = 5 + 14.4 \ e^{-0.175 (2 - \log N_o)^{2.5}} \quad \text{(A-10)}$$

where

$$N_o = \frac{f \delta}{171.5} \quad \text{(A-11)}$$

(171.5 = half of the speed of sound waves in air, in m/s)

$$\delta = \sqrt{(h_T - h_s)^2 + d_s^2} + \sqrt{(h_T - h_R)^2 + d_R^2} - \sqrt{(h_s - h_R)^2 + (d_s + d_R)^2} \quad \text{(A-12)}$$

for h- and d- values refer to Figure 6

For noise barrier segments with a smaller subtending angle, $\phi < 90°$, the segmental sound barrier attemation can be approximately calculated by

$$\Delta = 5 + 15\, e^{-c(d-\log N_o)^n} \quad \text{(A-13)}$$

where

$$c = 0.536 + 0.46\, x - 0.0974\, x^2 \quad \text{(A-14)}$$
$$d = 1.3 - 0.72\, x + 0.184\, x^2 \quad \text{(A-15)}$$
$$n = 1.9 - 0.325\, x \quad \text{(A-16)}$$

where

$$= \log(90°-\emptyset)-1$$

$$\text{strictly valid for } 30° \leqslant \emptyset \leqslant 80° \quad \text{(A-17)}$$

For $\emptyset<30$, use $\emptyset = 30°$ (conservative assumption)
for $\emptyset>80$, use actual $\emptyset$ up to 85°, beyond 85°, use solution for 90° or use diagram Figure 7. The calculation of N_o and δ remains the same as before, i.e. as in the solution for 90°.